KACST

FINAL REPORT: Application of Saudi Arabian Surface Radiation Flux Measurements for Validation of Satellite Remote Sensing Systems

Daryl R. Myers, Stephen Wilcox, Mary Anderberg
National Renewable Energy Laboratory, 1617 Cole Blvd, Golden CO 80401 USA
Saleh Alawaji, Naif Al-Abaddi, Mohammed bin Mahfoodh
King Abdulaziz City for Science and Technology Emir Abdul Road, PO Box 6086 Riyadh 11442 KSA

1.0 Introduction

From 1993 to the present (Dec 2002), King Abdulaziz City for Science and Technology (KACST) in Riyadh, Saudi Arabia and the U.S. National Renewable Energy Laboratory (NREL) conducted a joint solar radiation resource assessment project to upgrade the solar resource assessment capability of the Kingdom of Saudi Arabia. NREL assisted KACST with design and deployment of a high quality 12-station network in Saudi Arabia for monitoring solar total horizontal, direct beam, and diffuse radiation. One- and five-minute network data are collected and assessed for quality. 80% or more of the network data fall within quality limits of ±5% for correct partitioning between the three radiation components.

In May of 1997, NREL and KACST prepared a joint proposal responding to the National Aeronautics and Space Administration (NASA) Research Announcement NRA-97-MTPE-03 titled "Satellite Remote Sensing Measurement Accuracy, Variability, and Validation Studies".

The NREL/KACST proposal addressed the request for "type 2" projects, that "…enhance, supplement, and/or complement activities planned by the EOS Instrument and Interdisciplinary Science Teams to characterize and validate the accuracy of remotely-sensed geophysical parameters derived by the Instrument Science Teams from measurements by EOS satellite sensors in the AM-1 time frame. "

The project, "Application of Saudi Arabian Surface Radiation Flux Measurements for Validation of Satellite Remote Sensing Systems" was approved in Dec 1997 (FY 98) and was initially funded in Feb 1998. As described in our proposal abstract and the statement of work (Appendix A) the objectives of the project were to:

(a) Provide quality assessed Saudi Arabian surface solar radiation data stream of 5 minute, hourly, and monthly solar radiation data with assigned uncertainty; through an NREL Internet accessible link.
(b) Provide NASA with the highest accuracy solar radiation data obtainable for the Saudi Arabian climate by assisting Saudi Arabia to upgrade their measurement instrumentation to World Meteorological Organization (WMO) Baseline Surface Radiation Network (BSRN) Standards.
(c) Develop estimates of atmospheric properties (aerosols, water vapor) from Saudi Arabian measured data for comparison with the same NASA satellite derived properties.
(d) Participate in NASA sponsored satellite validation Science and Instrumentation Team workshops, meetings, and personal communications to NASA validation team contacts to facilitate the integration of the NREL data into NASA data formats and data flow into identified data archives.

As originally envisioned, the project was proposed to continue for a four-year period from 1998 to 2002. Delays in the launch of the TERRA spacecraft (EOS-AM-1) and funding limitations resulted in funding for a one year startup and implementation of the project in 1998, with continuing annual incremental funding to sustain data flow on a year by year basis from 1999 to 2002. KACST participated as a non-funded co-operative foreign partner. Table 1 shows the actual funding level over the period of the project (Jan 1 1998-Dec 31 2002). In 1998 KACST contributed $85,000.00 of their own funds for project equipment upgrades; described below. From 1999 to 2002, KACST provided in-kind labor for operating and maintenance (O&M) support for the Solar Village station, as well as the other 11 stations in the Saudi flux-monitoring network.

Table 1. Annual Funding Levels Joint NREL/KACST/EOS Validation Project

Year	US Funding ($US)	Saudi Funding ($US)	
1998	$197,262.00	$85,000.00	**Grand Total**
1999	$35,000.00	In Kind Operating	
2000	$35,000.00	In Kind Operating	
2001	$35,000.00	In Kind Operating	
2002	$35,000.00	In Kind Operating	
TOTAL	$337,262.00	$85,000.00	**$422,262.00**

2.0 Science Team Meeting Participation & Travel

Table 2 documents the NREL/KACST participation in NASA and World Meteorological Organization BSRN meetings over the course of the project.

Table 2. NASA/BSRN Meeting Participation by NREL/KACST participants.

Date	Meeting	Location	Contribution/Purpose
Sep 4-6 1997	EOS-AM1 Science Working Group for AM-1 Platform (**SWAMP**)	Hampton VA	Project Overview, Meet Instrument team representatives
Dec 3-5 1997	Shortwave AM-1 Planning meeting	Greenbelt MD	Co-ordination with CERES team; AERONET Project
May 14-23 1998	5th **BSRN** Science Team Meeting	Budapest Hungary	Saudi Station Status and archive co-ordination; Co-ordination with NASA AERONET and CERES Instrument team
Feb 2-3 1999	**SWAMP** meeting	Boulder CO	Describe Web Data Access CERES/MODIS/MISR team
May 27-29, 1999	19th**CERES** Science Team Meeting	Williamsburg VA	Surface and Atmosphere Radiation Budget (SARB) working group; Radiometer offsets & calibration issues
10-13 Apr 2000	EOS-AM/Terra Instrument Working Group (**IWG**) Meeting	Tucson AZ	Poster Presentation, Data Processing and posting; web access; ORNL MERCURY access
23-24 Oct 2000	HDF Workshop	Greenbelt, MD	EOS Data Processing tools
Jan 14, 2001	EOSDIS Training	Albuquerque NM	Access to EOS AM-1 Data
May 28-31 2002	7th **BSRN** Science Team Meeting	Regina, SK	BSRN Saudi station archive processing and status; Radiometric corrections

In addition, the NREL team (D. Myers, S. Wilcox, and J. Treadwell) traveled to KACST in Sep 1998 to install BSRN upgrade equipment and train Saudi participants in the O&M of KACST purchased BSRN upgrade equipment. NREL-developed software, training, and manuals for data collection and archiving were delivered to KACST during the visit. In addition, the team assisted KACST with installation of a NASA provided CIMEL sunphotometer to supplement the broadband radiation measurements with aerosol optical depth and water vapor estimates (see section 3, below)

3.0 Solar Village BSRN Station Upgrade

KACST operates a 12-station solar radiation network designed with the assistance of NREL. Each station measures global, direct, and diffuse solar radiation along with ambient temperature and relative humidity. Table 3 lists the stations and the date of initial operation. Table 4 lists instrumentation at all sites and estimated uncertainty in flux components after NREL applies corrections for known radiometer characteristics.

Table 3. Station Locations and Operational Dates**.**

STATION	LATITUDE	LONGITUDE	ELEVATION (meters)	Date Initial Operation
Solar Village	24.91	46.41	650	NOV 1994
Qassim	26.31	43.77	647	NOV 1994
Al Ahsa	25.30	49.48	178	JAN 1995
Wadi Al-Dawasser	20.44	44.68	701	APR 1995
Abha	18.23	42.66	2039	JUN 1995
Gizan	16.90	42.58	7	JUN 1995
Sharurah	17.47	47.11	725	JUN 1995
Jouf	29.79	40.10	669	AUG 1995
Qaisumah	28.32	46.13	358	AUG 1995
Tabouk	28.38	36.61	768	AUG 1995
Madinah	24.55	39.70	66	SEP 1995
Jeddah	21.68	39.15	4	MAY 1996

Table 4. Instrumentation common to all 12 Saudi monitoring stations.

Parameter	Ambient Temperature	Relative Humidity	Global horizontal solar Irradiance	Direct Beam Solar Irradiance	Diffuse Horizontal Solar Irradiance	Solar Tracker: Direct Beam; Diffuse Tracking Disk	Data Logger
Uncertainty (after corrections)	+/- 0.5 Deg C	+/- 2.5%	+/- 1.0% (+/- 10 W/m^2)	+/- 1.0% (AHF Cavity)	+/- 3.0% (+/- 6.6 W/m^2)	+/- 3.0° per day	0.2% Full Scale

Since the EOS Validation project participants found the BSRN data specifications stringent enough for validation purposes, an important objective of our validation project was to upgrade the Solar Village network site, and calibration facility for the KACST network, to meet those specifications. This required purchase and deployment of instrumentation for measuring upwelling and downwelling short- and longwave radiation, an absolute cavity radiometer for direct beam data, and higher time resolution (1 minute versus the network 5 minute reporting interval) data collection. KACST purchased the required equipment using approximately $85,000.00 of KACST funds to specifically support this aspect of the project.

The KACST-purchased upgrade equipment included two Eppley Laboratories model PIR pyrgeometers for up- and down-welling longwave; an additional Eppley Model PSP for upwelling shortwave (albedo) measurements; an Eppley Hickey-Frieden Absolute Cavity Radiometer configured for continuous all-weather operation, a precision computer controlled BRUSAG solar tracker, an additional Campbell Scientific CR-10 data logger for collecting longwave and albedo data. This equipment is shown in figures 1 and 2 below. The upwelling measurements were mounted on a tower at 30 meters (100 ft), meeting BSRN specifications for upwelling "footprints" below the instruments. KASCT also purchased an Eppley Model 8-48 black-and-white pyranometer to measure reference diffuse irradiance more accurately during calibrations of network pyranometers at the Solar Village central calibration facility. This removes a thermal offset error of approximately 5.0 W/m^2 (0.5%) from the resulting radiometer

Figure 1 All-weather absolute cavity radiometer (right) and shaded infrared radiometer (top left) on BSRN Brusag tracker at the Solar Village.

Figure 2. Installing IR radiometer in NREL-designed fixture for upwelling IR measurements. Shortwave upwelling radiometer (PSP) on opposite arm.

calibration factors. The fundamental uncertainty in the Saudi network fluxes has been established at ±10.0 W/m² for clear skies, and ±6.6 W/m² for cloudy (diffuse) conditions.

3.0 NASA AERONET Sunphotometer at the Solar Village

NASA/EOS CERES, MODIS, and MISR investigators were extremely interested in data for the aerosol optical depths in a desert environment. The NREL took the initiative with Brent Holben, the NASA AERONET project manager, to obtain the loan of a NASA CIMEL C-318 sunphotometer (Cimel Electronique 172, rue de Charonne 75011 Paris, France) to KACST for direct aerosol optical depth and precipitable water vapor measurements. Figure 3 shows the instrument as installed on the Solar Village calibration facility roof. Data is collected hourly and transmitted via satellite to the Aeronet internet site http://aeronet.gsfc.nasa.gov:8080/ at Goddard Space Flight Center (GSFC) in Greenbelt Maryland. Throughout the project, NREL coordinated installation, training, calibrations, and instrument change outs between GSFC and KACST. Figure 4 shows a data sample from the Solar Village site.

Figure 3. Cimel Sunphotometer (lower center) installed at Solar Village Station Site, Sept. 1998

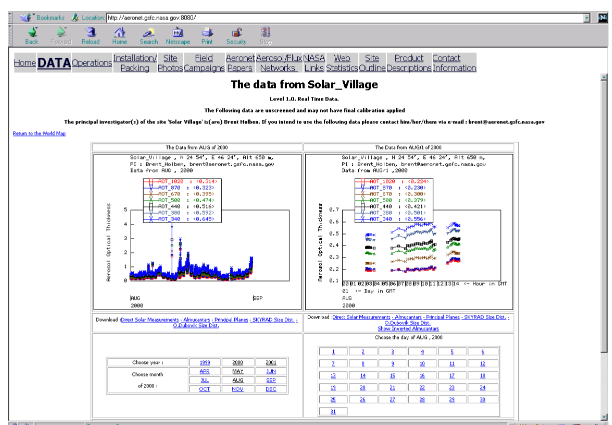


Figure 4. Cimel Sunphotometer Data on the AERONET web site.

4.0 World Wide Web Internet Data Access

NREL developed an Internet home page for the Saudi radiation data at **http://rredc.nrel.gov/solar/new_data/Saudi_Arabia/.** Five-minute average quality assessed for all twelve stations were first made available at that location in May of 1999. NREL developed quality assessment routines for evaluating the BSRN data in a fashion similar to that applied to the twelve station network data. Figure 5 shows the homepage, the clickable map interface to access network and BSRN data directly, and links describing file formats.

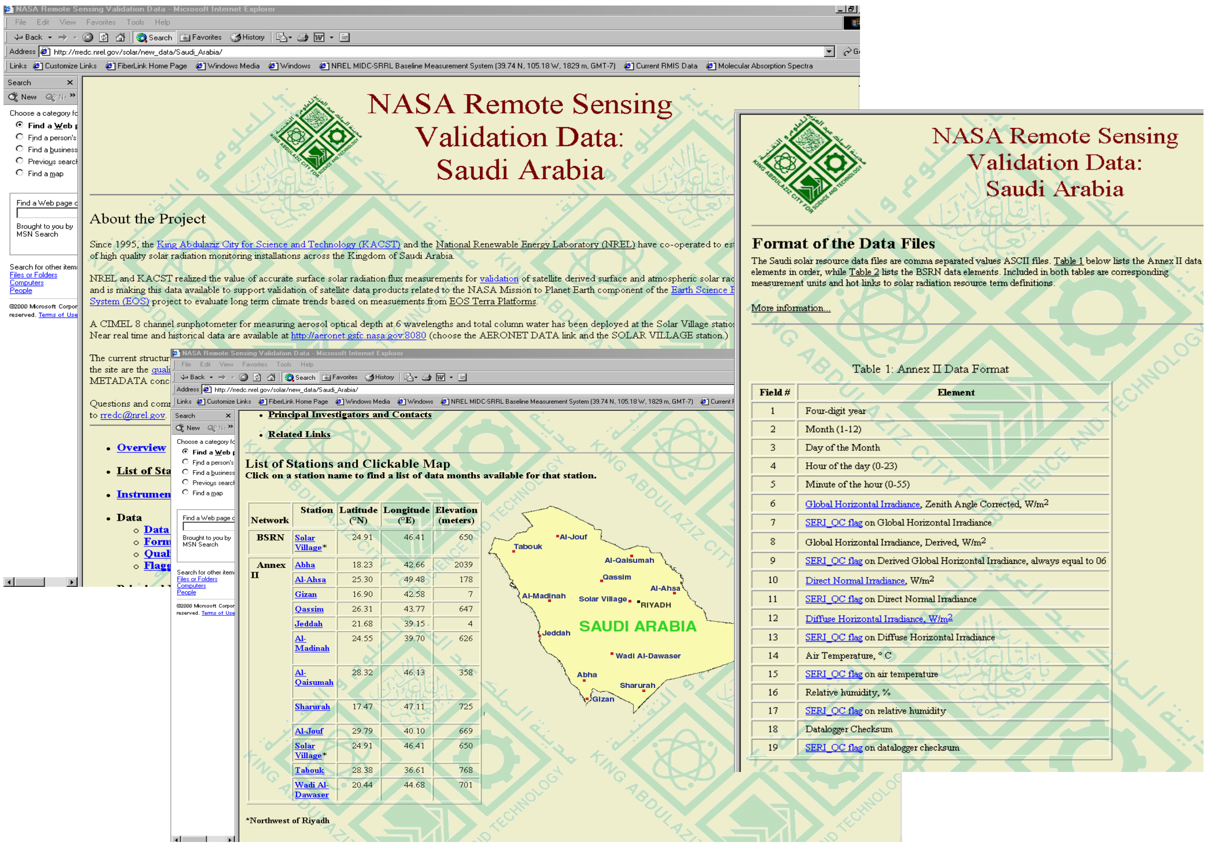


Figure 5. NREL internet site for accessing quality assessed Saudi network and BSRN data in comma delimited format developed in summer of 1998.

NREL also developed an extensive software package to reformat the Saudi BSRN site data into the prescribed format for submission to the BSRN archive for Riyadh. A BSRN archive account was established at the ETH web site at http://bsrn.ethz.ch in Zurich for submissions of reformatted data. During the summer of 1999, we updated the NREL web site to include the more extensive BSRN data sets, network calibration histories, and zenith angle correction metadata. Figure 6 shows the links to additional Internet pages developed for access to this metadata. In particular, the calibration and deployment history provides information on the corrections applied to global horizontal pyranometer flux data. The history displays the "calibration vector" of responsivities for each of 10 zenith angle bins from Z=0° to Z=90° that are arrived at during each annual calibration event at KACST. These zenith angle dependent responsivities, or calibration factors, have been applied to the collected global horizontal (pyranometer) data, which are posted on the station/year/month specific data file. We also integrated the NREL internet site into the

Oak Ridge National Laboratory (ORNL) MERCURY access system maintained by Oak Ridge National Laboratory at http://mercury.ornl.gov/ornldaac Carroll Curtis of ORNL updated the interface to make access to the data sets much easier (figure 7).

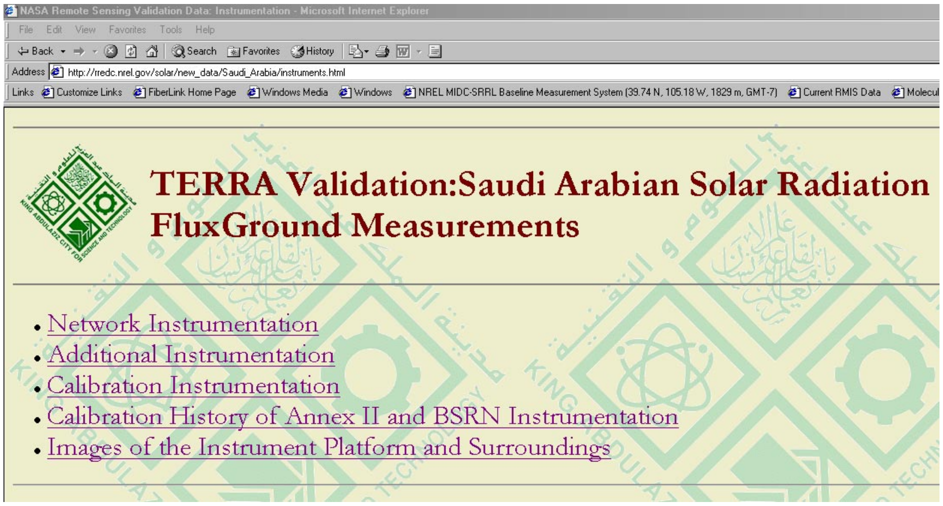


Figure 6. Additional metadata links, including calibration and deployment history of instrumentation.

Under the MERCURY URL mentioned above, one selects “Data Set Titles” and then “NASA Remote Sensing Validation Data for Saudi Arabia Solar Radiation Network” and the page in figure 7 appears. Each individual station can then be accessed with metadata and ancillary information presented in a more compact and straightforward form.

In November of 2002, NREL accomplished the non-trivial task of reformatting all Solar Village BSRN data to date, and successfully submitting the data to the archive (Station Identifier **SOV**). NREL will provide KACST with the reformatting software package, and KACST will take over the process of submitting data updates to the BSRN archive soon after the termination of the project.

5.0 Data comparisons

The NREL team attended training on both EOS Data and Information System (EOSDIS) and Heirarchical Data Format (HDF) to be able to gain access to and analyze EOS CERES and MODIS data sets for comparison with the NREL/KACST data sets. As of the time of this report, surface flux estimates for these instruments are not available, though planned. For example, an EOSDIS search of CERES data products at http://eosdatainfo.gsfc.nasa.gov/eosdata/ssinc/ceres_dataprod.shtml show surface flux estimates for Chesapeake Lighthouse Atmospheric Monitoring Station (CLAMS) and the Atmospheric Radiation Monitoring (ARM) site; but not over broader geographic coverage. This is understandable, as the CLAMS and ARM site can provide excellent continental and marine “calibration” sites for the instruments. The Saudi sites will be of future interest in evaluating the effectiveness of estimating algorithms over desert sites.

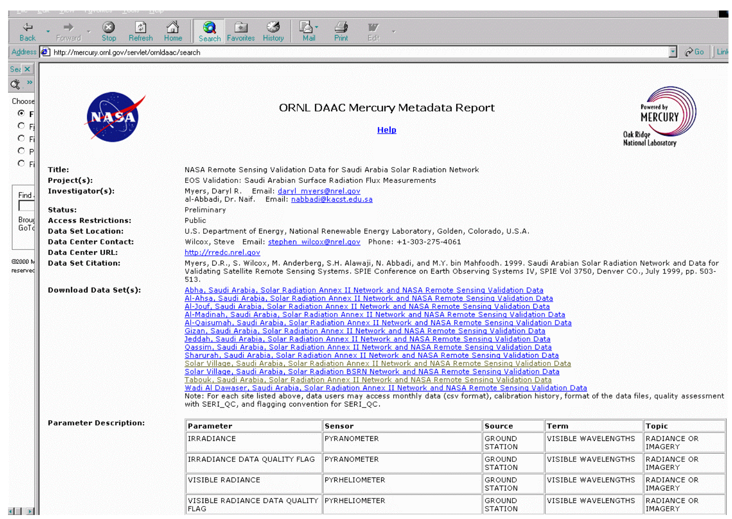
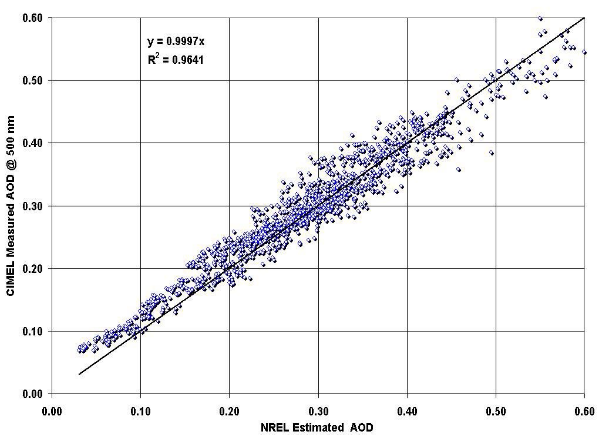


Figure 7. ORNL Mercury access page for KACST/NREL solar radiation network data.

Using EOSDIS search parameters for solar radiation flux on the EOSDIS gateway page for a region covering the Arabian Peninsula results in ERBE-like and top of atmosphere products, but no surface flux estimates yet. NREL plans to monitor the availability of surface flux estimates from these platforms and compare our measurements with surface flux estimates when they become available. The team will remain available to address concerns of instrument teams after the conclusion of the project; as KACST will continue to supply NREL with data for post-processing and posting on the NREL website and in the BSRN archive.

We have compared NREL methods for estimating aerosol optical depth and water vapor with the CIMEL based sunphotometer measurements. Figures 8 and 9 show the correlation between one month of Solar Village quality assured sunphotometer measurements and NREL estimates of AOD and total precipitable water vapor. The correlation of NREL AOD estimates with the NASA measurements is better than 0.96. The correlation between total water vapor estimates is low (0.4), since the "signal" for water vapor at the Solar Village station is low (less than 2.5 cm). However, the linear relationship between the two measurements and estimates has a slope within 0.8% of unity.



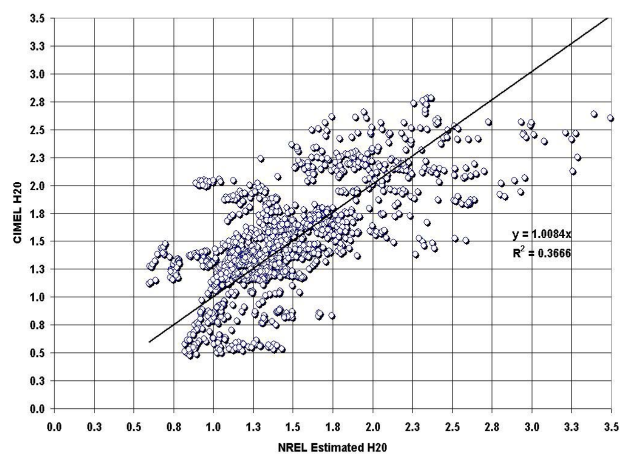


Figure 8 Correlation of NREL CIMEL estimates of Aerosol Optical Depth (AOD).

Figure 9 Correlation of NREL and CIMEL estimates of total water vapor.

Figure 10 is a histogram, showing the mean difference between NREL and CIMEL AOD is 0.01 . Most measured optical depths are considered very accurate if they have uncertainty of 0.03 OD or less.

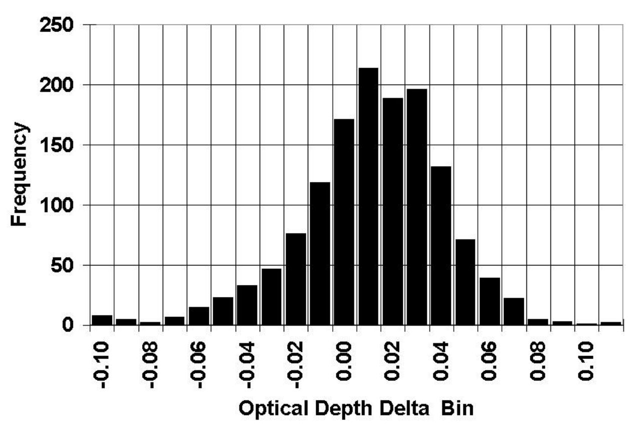


Figure 10. Histogram of differences between CIMEL measurements and NREL estimates of aerosol optical depth for March, 2000.

6.0 Citations

The CERES EOS Team cites the project in several recent papers as contributing to the CERES Surface and Atmospheric Radiation Budget (SARB) validation activity. The project has been cited in the following;

Rutan, D. A., F. G. Rose, N. Smith, and T. P. Charlock, 2001: "Validation Data Set for CERES Surface and Atmospheric Radiation Budget (SARB)". GEWEX News, Vol. 11, No. 1 (February), pp. 11-12. Available at www.gewex.com under "Newsletter".

Rutan, D. A., F. G. Rose, N. Smith, and T. P. Charlock, 2001: "CERES/ARM Validation Experiment. Eleventh ARM Science Team Meeting Proceedings (Atlanta, 19-23 March 2001)." 4 pp. Available at www.arm.gov under "Publications".

CERES has used NREL data in reports and science team presentations. At http://asd-www.larc.nasa.gov/ceres/docs.html : "Validation Documents" and (SARB) "PDF". There are several figures based on surface radiometric data from them. The References include Myers, and other surface measurement investigators.

7.0 Publications

Reda, I., T.L. Stoffel, D.R. Myers, "Establishing the Clear Sky Diffuse Irradiance Reference for Broadband Radiometer Calibration" Submitted to Solar Energy, Sep, 2002.

Myers, D.R., T.L Stoffel, S. Wilcox, I. Reda, A. Andreas., "Recent Progress in Reducing the Uncertainty in and Improving Pyranometer Calibrations" *ASME Journal Solar Engineering*, Vol 124, No. 1, Feb, 2002 pp 44-50.

Reda, I., J.R. Hickey, T. Stoffel, D. Myers, "Pyrgeometer Calibration at the National Renewable Energy Laboratory (NREL)" Journal of Atmospheric and Solar Terrestrial Physics, Vol 64. No 15. Aug 2002. pp. 123-1529

Wilcox, S., N. Al-Abaddi, D. Myers, M. bin Mahfoodh, "Improving Global Solar Radiation Measurements Using Zenith Angle Dependent Calibration Factors" Proceedings of the American Solar Energy Society Annual Meeting, Forum 2001, April 21-25, 2001, Washington, D.C. R. Campbell-Howe, ed.

Wilcox, S., N. Al-Abaddi, D. Myers, M. bin Mahfoodh "Using Irradiance and Temperature to Determine the need for Radiometer Calibrations" Proceedings of the American Solar Energy Society Annual Meeting, Forum 2001, Washington, D.C. April 21-25, 2001, R. Campbell-Howe, ed.

Abbadi, N.M., S.H. Alawaji, M.Y. bin Mahfoodh, D.R. Myers, S. Wilcox, M. Anderberg, "Saudi Arabian Solar Radiation Network Operation Data Collection and Quality Assessment" Renewable Energy, Vol 25 #2, Feb 2001.

Stoffel, T.L, I Reda, D.R. Myers, D. Renne., S. Wilcox, J. Treadwell, "Current Issues in Terrestrial Solar Radiation Instrumentation for Energy, Climate, and Space applications." *Metrologia*, 2000, 37, 399-402.

Myers, D. R., S. Wilcox, M. Anderberg, S. Alawaji, N. Al-Abbadi, M. bin Mahfoodh. Saudi Arabian Solar Radiation Network for Validating Satellite Remote Sensing Systems. Earth Observing Systems IV, Annual Meeting of Photo-optical Instrumentation Engineers # 3750, Denver Co, Society of Photo-optical Instrumentation Engineers, 1999. pp 503-513.

Reda, I., and D. Myers, "Calculating the Diffuse Responsivity of Solar Pyranometers", NREL TP-560-26483, National Renewable Energy Laboratory July 1999.